INS/GPS for Strike Warfare Beyond the Year 2000

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Abstract

This paper presents a review of Inertial Navigation Systems (INS) and the Global Positioning System (GPS) as a key technology for Strike Warfare beyond the Year 2000. The paper reviews the functionality that INS/GPS provides the Missile Guidance, Navigation and Control (GNC) designer plus the requirements associated with this functionality. Existing systems on the market are reviewed and new systems that can be expected to enter the market in the 2000 to 2010 time frame are discussed. System issues associated with the use of this hardware and trends in system integration methods are reviewed. The paper concludes with a discussion of the likely future uses of INS/GPS in precision strike missiles.

Applications of INS/GPS in Strike Warfare

Two primary uses of INS/GPS in Strike Warfare are low cost guidance tailkits for dumb bombs and midcourse guidance for long range precision strike missiles. Tailkits such as JDAM that include an integrated INS/GPS can be attached to dumb bombs and reduce the dispersion of the bombs to the inherent accuracy of the GPS system (15 Meter CEP). These inexpensive guidance kits which do not require a seeker provide a precision strike capability at a much lower cost than weapons requiring a terminal seeker. These INS/GPS guided weapon are only useful for a portion of the fixed targets of interest to Strike Warfare but they provide a very valuable operational capability.

INS/GPS also provides accurate midcourse guidance for long range standoff weapons attacking fixed targets. The INS/GPS midcourse guidance system can guide the weapon accurately enough that when the seeker turns on, the target will be within the field of view of the seeker. There is no need to scan the seeker back and forth to locate the target. The seeker turns on and expects to find the target within the current seeker field-of-view (FOV). After the seeker turns on, acquires and tracks the target, the INS/GPS tracks the target location between target updates. In the presence of cloud cover, INS/GPS guides the weapon through the clouds until the seeker has a clear view of the target. In this scenario, the INS/GPS is viewed as providing a through the clouds attack capability.

Engageable Threats

The target types that lend themselves to being attacked by INS/GPS guided weapons are primarily stationary targets. Fixed targets can be located and surveyed using reconnaissance assets. The coordinates of these fixed targets can be loaded into the weapon computer and the onboard INS/GPS can guide to the target coordinates.

Special types of fixed targets that cannot be easily surveyed prior to the mission can also be attacked with INS/GPS. An antiradiation missile can use INS/GPS to guide to the last computed target coordinate should the antiradiation seeker lose the target. This can provide an important operational capability to deal with the loss of a threat signal during the missile terminal guidance phase.

Moving or relocatable targets cannot be attacked with a weapon guided solely by INS/GPS. These targets require a seeker to correct for target location uncertainty. However, INS/GPS can help reduce the complexity of the relocatable target acquisition problem for the seeker of choice.

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Response Time

Missile response time from power up to ready for launch can be impacted by the presence of an INS/GPS system. The inertial navigation system must go through an alignment process to find local level and north that can take several minutes. GPS must acquire the satellite signal and decode the signals that can take minutes to accomplish. An integrated INS/GPS can, therefore, become a limiting factor in missile response time.

Two distinct types of alignment scenarios exist for tactical missiles depending on the missile system approach taken to handling this requirement. The INS/GPS system can be aligned on the runway prior to the aircraft taking off. Alignment in this case is easier because the aircraft is stationary, but once aligned, power must remain on the weapon through the aircraft flight. The second approach is in-air alignment that requires aligning the weapon INS/GPS system to the aircraft INS/GPS system. This second approach assumes a modern digital interface to the weapon store location and many older aircraft lack this digital bus. Newer aircraft include a digital bus to the weapon and in-air alignment will grow in popularity in the future.

When performing in-air alignment, the accuracy of the alignment is enhanced by aircraft maneuvers during the alignment process but this approach is unpopular with pilots and could be totally unacceptable in the case of stealth aircraft. Ultimately the in-air alignment accuracy is limited by flexure of the aircraft structure between the aircraft INS/GPS and the weapon INS/GPS. Since GPS acts as a separate external alignment device for the INS, this structural flexure problem is more of a concern when using free inertial systems that do not include GPS.

Type of Inertial Products

Inertial products come in various configurations. At the lowest level are the inertial instruments that measure the actual missile motion. Angular motion is measured using a gyroscope whose digital output is a linear function of the rotation rate about its input axis. Each gyroscope measures one axis of rotation so three gyroscopes are required to measure the 3 dimensional rotation rate vector of the missile (pitch, yaw and roll). Translational motion is measured using accelerometers whose output is a linear function of the translational acceleration along its input axis. Three accelerometers are required to measure the 3 dimensional acceleration vector of the missile. Older missiles used gyroscopes and/or accelerometers in the missile autopilot to maintain stable missile flight characteristics. Gyroscopes were also used to stabilize the seeker optics or antenna. Figure 1 illustrates the difference between an IMU (Figure 1a) that is a cluster of 3 gyroscopes and 3 accelerometers required to measure the complete missile rotation and acceleration vectors and an INS (Figure 1b) that computes location on the earth using IMU outputs. A missile can use an IMU for autopilot functions and seeker stabilization without adding the computer necessary to compute location on the earth. The trend is towards integrated INS/GPS systems. GPS requires a complete navigation system to maintain synchronization with the satellite signals and the INS needs GPS to keep the navigation error from growing without bound as illustrated in Figure 1b.

Types of INS Systems

Figure 2 shows pictures of a typical aircraft integrated INS/GPS system and a typical tactical missile INS. There is obviously a significant size difference. The aircraft INS has a larger IMU and this translates into more accurate inertial sensors. The aircraft INS must provide significantly more functionality since an aircraft has many missions and mission packages with a complex set of INS requirements. The aircraft INS holds more electronic circuit cards and often uses temperature stabilization for the inertial measurement cluster. In contrast with the aircraft INS, the missile INS is more limited in its functionality and scope. It uses smaller sensor and smaller electronics. The loss of navigation accuracy with time in the absence of GPS is an order of magnitude higher in the tactical missile INS than the aircraft INS. Since the INS includes an IMU a tactical missile INS can provide the signals required by the missile autopilot, the seeker optics/antenna stabilization, midcourse navigation and terminal guidance requirements.

One trend in tactical missiles that will help reduce the size and cost of tactical INS is to avoid redundant hardware and software through a system architecture that emphasizes a high degree of system integration.

Modern missiles will use one central power supply or one central processor eliminating the need for the INS to have a separate power supply or processor.

Example of Current Inertial Products

Figure 3 shows several pictures of inertial products found at various websites on the internet. Many systems use laser gyroscopes that were developed over a 20 year time frame. The laser gyroscope on the left of figure 3 is the world largest and helps give a better view of the gyroscopes structure. A laser gyroscope uses two counter rotating laser beams that interfere with each other when they meet at one corner of the cube. The degree in interference is a function of the rotation rate about an axis normal to the laser gyroscope. A smaller tactical missile grade laser gyroscope is also shown in figure 3. Figure 3 also shows a more traditional spun rotor gyroscope using a rotating mass driven by a motor. Accelerometers are still primarily the force balance or mass on a spring design. A triad of accelerometers is shown on the bottom right of figure 3. Figure 3 includes one example of and inertial cluster including three orthogonal gyroscopes and three orthogonal accelerometers.

Trends in Inertial Sensors

There are new types of inertial sensors being developed that are expected to enter the market place in the next 5 - 10 years. This includes a fiber optic gyroscope similar to a laser gyroscope but capable of achieving a longer path length by using a spool of fiber optic cable. A fiber optic gyroscope can achieve the same sensitivity as a laser gyroscope but in a much smaller package. A newer technology that has significant commercial market potential is the Micro-Electro-Mechanical Systems (MEMS). MEMS is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through the utilization of microfabrication technology. These MEMS sensors can be packaged in very small sizes and have the potential for high rate/low cost production. A key factor in the ability of tactical INS manufacturers to build lower cost products will depend on the success of MEMS technology and the development of a commercial market for inertial sensors.

Initially the newer inertial sensors will lack the accuracy of the older sensor designs, but since GPS can work with lower accuracy inertial systems, this will not limit the introduction of these new sensors. As the manufacturing processes for these newer sensors mature, they will reach and perhaps surpass the performance of the current inertial sensors.

Missile Guidance Functionality Impacted by INS Performance

An INS can support many different parts of an integrated missile guidance, navigation and control (GNC) design. This includes:

- source of autopilot measurements of missile short term motion
  - missile rotational rate about the weapon center of gravity and acceleration through the weapon center of pressure
- source of midcourse guidance information on missile location relative to the expected target location
- source of seeker measurements of missile motion required to support
  - sensor compensation
    - imaging sensor
  - image motion stabilization
    - radar
      - range and/or velocity to scene center
    - synthetic aperture radar - image formation
      - short term missile motion
  - sensor cueing
    - point where the target is expected to be - sets search area

- ATR cueing
    - fixed target approach angles plus range to target
- multisensor fusion
    - change in missile aspect between different sensor collection times
- source of guidance commands between sensor updates
    - guides after sensor goes blind

All these GNC functions have different requirements that must be integrated into the total design requirement for the integrated INS/GPS. Balancing these different design requirements without growth in the cost of the INS/GPS system is a very challenging design problem.

Missile INS Need Statement

A missile needs an INS/GPS primarily to guide the missile to the target area when the launch range is beyond lock-on before launch ranges or the missile does not contain a seeker. The missile also needs an INS/GPS system to keep the missile seeker pointed at the target during missile maneuvers. As already mentioned to guide a weapon over long ranges with a tactical grade INS would require a very expensive INS with low drift rate or GPS as a navigation update device. Many new sensors also have short acquisition range so there isn't much time for the seeker to scan around and search for the target. An accurate INS/GPS system can often guide the missile to the target to sufficient accuracy that the target will be in the sensor field-of-view at sensor turn-on.

A secondary missile need for an INS in the case of fixed targets is providing the automatic target recognition (ATR) system information on the target viewing angles and range to the target at sensor turn-on. This information significantly reduces the complexity of the ATR problem for fixed targets. This need for an INS/GPS to reduce ATR complexity is not as well understood by missile designers today nor is it understood how to exploit INS/GPS to reduce the complexity of the moving or relocatable target ATR problem.

Missile Performance Metrics Impacted by INS/GPS Performance Metrics

The performance of the integrated INS/GPS system impacts several important missile level performance metrics. The most obvious metric that is impacted is the missile circular error probability (CEP). This is especially the case for missiles that are totally guided using an INS/GPS. In the case of INS/GPS guidance the CEP is limited by a combination of GPS accuracy and target location accuracy. Normally the CEP of an INS/GPS guided weapon is on the order of 15 meters.

INS/GPS performance also impacts the maximum weapon range. This is especially the case when GPS is not used and midcourse guidance is free inertial. In the case of INS/GPS the impact is only seen if the missile operational scenario includes a GPS jammer in the target area. GPS has made it easier to fly longer midcourse navigation ranges prior to seeker turn-on.

INS/GPS can provide a degree of adverse weather performance. INS/GPS weapons can attack fixed targets through the clouds. Laser guided weapons or optical guided weapon cannot penetrate cloud cover and must acquire the target after penetrating the cloud cover. INS/GPS also helps to hold the missile on the target when the seeker line of sight to the target is interrupted for any reason or the seeker temporarily locks onto a false target.

INS/GPS performance impacts the type of target that can be attacked. Fixed targets are very compatible with INS/GPS guidance. Relocatable or moving targets require a seeker but INS/GPS can reduce the seeker search area. Therefore, the INS/GPS performance will impact the performance of the missile across the total mission target set.

INS/GPS performance impacts warhead effectiveness. The INS/GPS makes it easier to achieve the terminal impact condition required for maximum warhead effectiveness. This includes the impact angle and angle of attack of the missile at target impact.

INS Error Model

Figure 4 shows a simple error model for the INS system. Since the inertial measurement devices measure rotational rate and translational acceleration, the computer in the INS must integrate these measurements to obtain missile attitude, translation velocity and position. The block diagram shown in figure 4 is made up of several integrators. The errors associated with the different inertial sensors pass through a different number of integrators. The more integrators the errors pass through, the faster the associated position error grows with time. For example, gyro bias is integrated to create a tilt error that multiplies gravity to create an acceleration bias. The acceleration bias associated with the gyro bias induced tilt error is double integrated to create a position error that grows with the third power of time. The velocity bias error only passes through one integrate and grows with the first power of time.

It is possible to misinterpret these different errors and their impact on position error as a function of time. For short time of flights, the velocity bias dominates even though it grows only linearly with time. Gyro drift dominates for long times of flight since it grows with the cube of time. One reason is that velocity bias is usually larger than the acceleration bias and it is usually larger than the gyro bias.

All the INS errors can in general be approximated as an error of the form kt^n where k is a constant including the error term, t is time and n is the power 0, 1, 2 or 3. These simple error models are very compatible with computing INS errors using a handheld calculator or a spreadsheet. Computing the errors when GPS is used to update the INS is even simpler since the position and velocity errors are fixed by GPS in the steady state and that is normally the phase of interest to the missile designer.

Figure 5 shows the position error growth as a function of time caused by acceleration bias and gyro drift starting from a perfect alignment. Note that for the short term, there is little difference between these INS units. In the long term, the curves diverge considerably because of the difference in gyro drift rates. This long term drift is only important for missile designs that do not include GPS or in the case of GPS jamming.

Missile Motion and INS Performance

So far, all the discussions about the INS/GPS system has dealt with very low frequency motion which can be represented by powers of time. Navigation systems traditionally are concerned with low frequency motion measurement as illustrated in figure 6. Imaging sensors such as synthetic aperture require the measurement of motion frequencies higher than frequencies traditionally of interest to navigation designers. These sensors need an accurate measurement of short term motion and even require measurement of missile vibration that might be induced by the propulsion system or actuator motion. As figure 6 illustrated, vibration can extend far beyond traditional motion frequencies. Accurately measuring this high frequency motion is a new requirement for INS designers and not yet fully understood by many.

As figure 7 illustrates, measuring the higher frequency motion of a missile requires a higher sampling rate and falls more into the area of expertise of the digital signal processing designer than the navigation designer. This high frequency motion measurement must concern itself with small changes in position on the order of a radar wavelength. A need exists to balance the INS design between the needs of the midcourse navigation system and the imaging seeker needs.

New Tactical Grade INS Systems

Figure 8 shows a sample of new or proposed tactical grade INS units based on emerging technologies. Perhaps only one of these new units will reach high rate production. These units will probably not fill all the needs of future tactical missiles. The missile GNC designer will have to develop design architectures that fit

these new INS units at costs consistent with new procurement guidelines. There will be many challenging design problems but these products will help reduce the cost of future tactical missiles.

Integrated INS/GPS Cost

Since cost is very important in the current military acquisition approach for tactical missiles, it is necessary to point out that cost includes not only the selling price but also the warranty cost and repair cost. It is not unusual today for the military to require a warranty on new missile and require the supplier to maintain and repair the weapon. Inertial products developed for the commercial market place may not be compatible with a 10, 15 or 20 year warranty. Validating a warranty may take a sizeable investment and require some redesign of units currently under development.

Tied to cost is risk management. There are many risks associated with phasing a new INS into a production missile. The trend is to go with an INS that is already in production so new INS system will first be introduced for those applications that have strong needs such as small package sizes below those currently produced.

Summary and Conclusion

In summary, integrated INS/GPS systems are a key technology for tactical missiles and will provide increasing levels of functionality as missiles include advanced imaging seekers and seekers incorporate automatic target recognition. This trend towards increased use of integrated INS/GPS systems is supported by the development of small tactical grade INS units using MEMS and fiber optic technology. INS designers have to increase their understanding of new INS requirement created by imaging infrared and radar sensors.

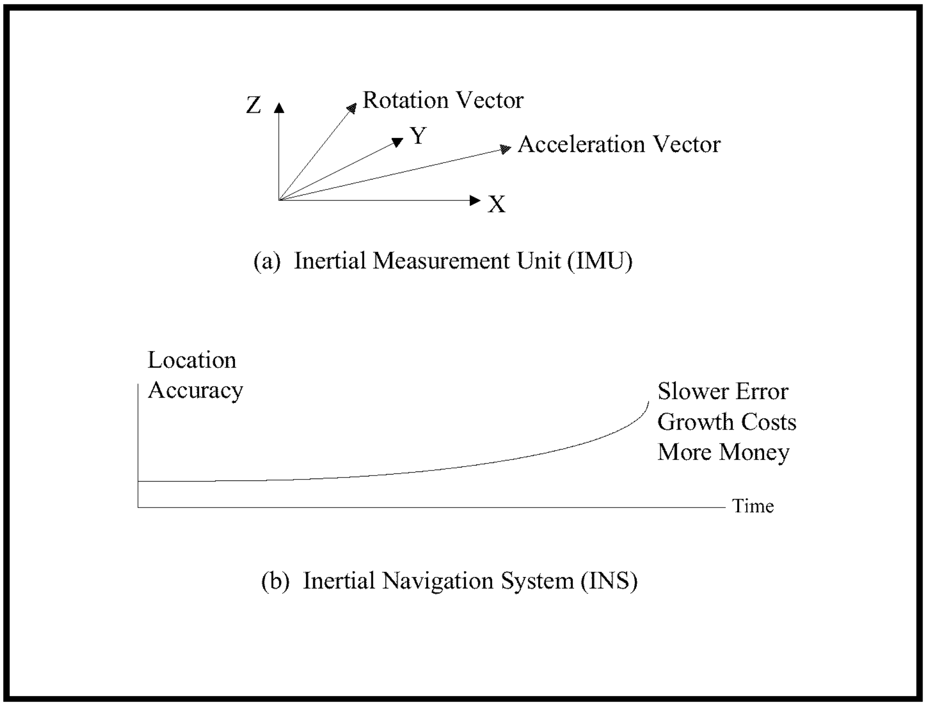
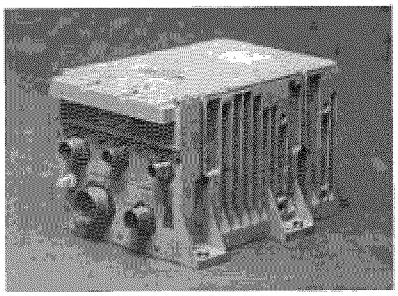
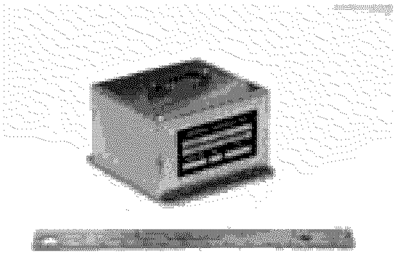


Figure 1. IMU versus INS



(a) Aircraft Grade INS



(b) Tactical Grade INS

Figure 2. Size Variation in INS Systems

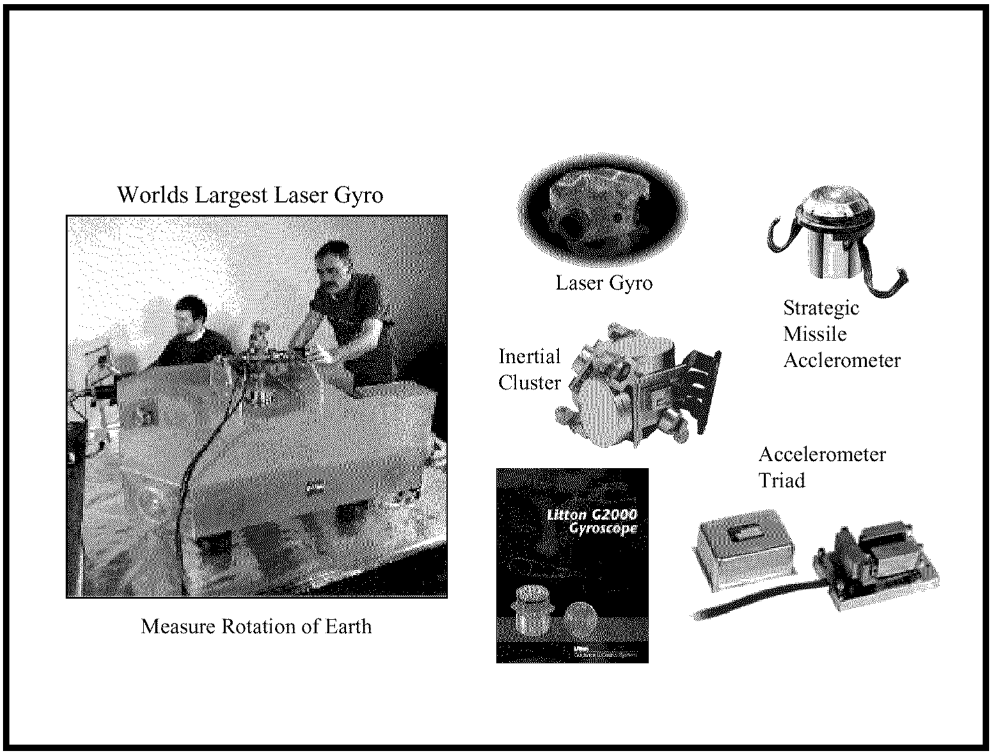


Figure 3. Sampling of Inertial Products

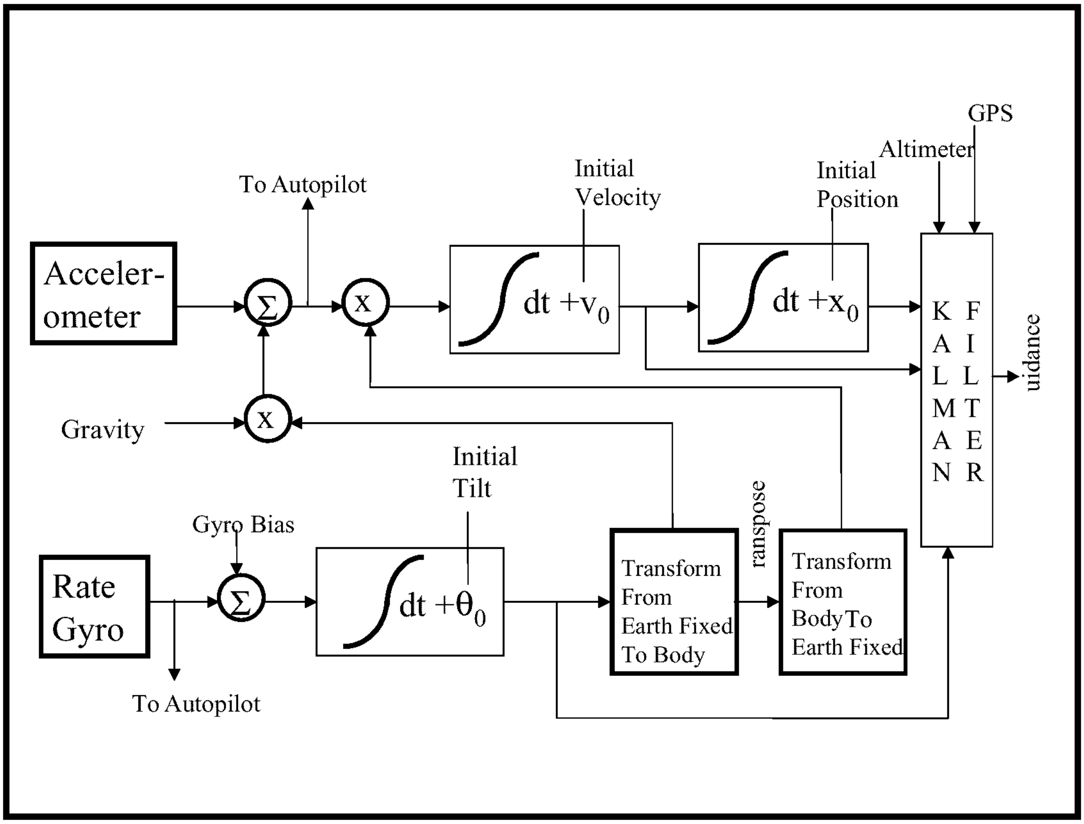


Figure 4. INS Error Model

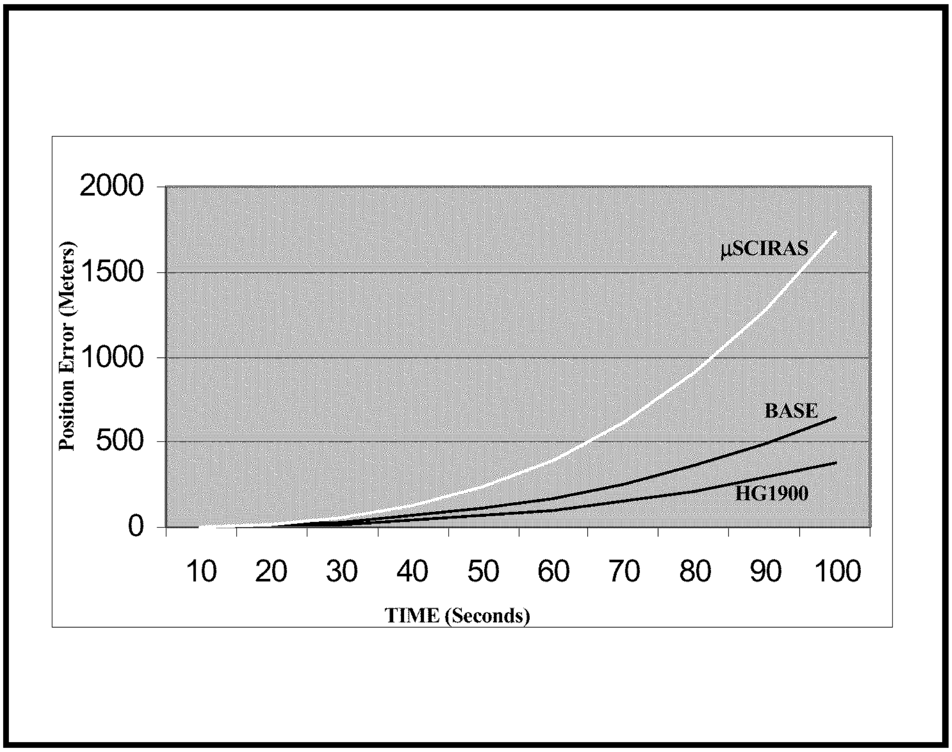


Figure 5. Representative Tactical Grade INS Position Growths

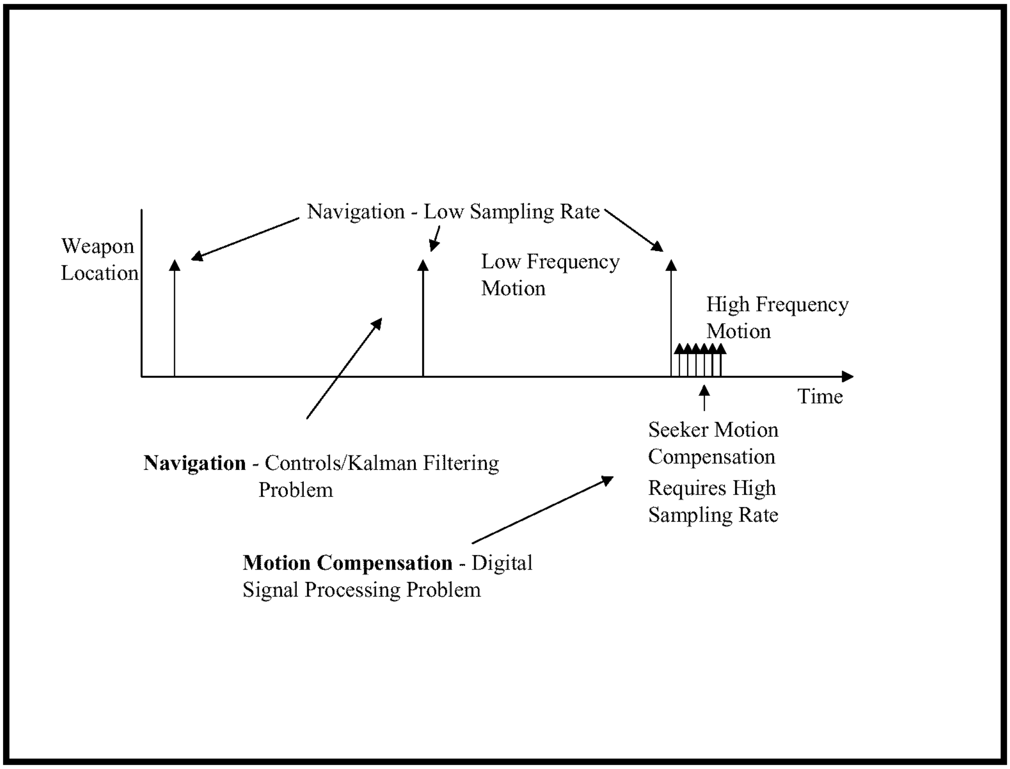


Figure 6. Motion Signal Processing Design

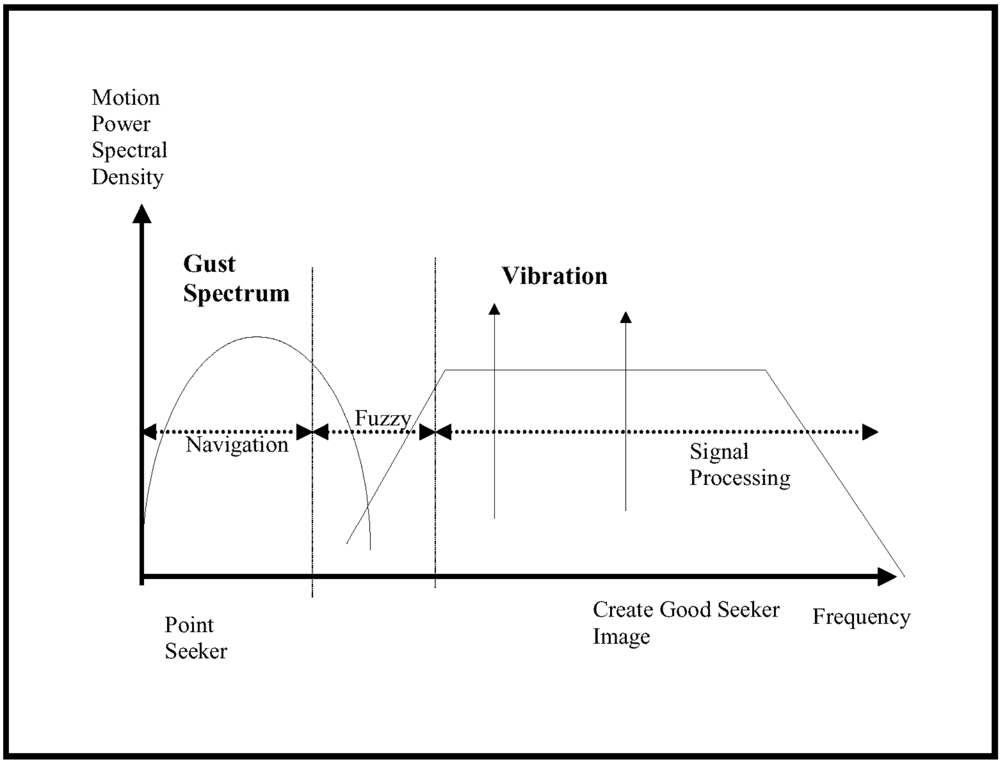


Figure 7. Missile Motion Bandwidth and INS Function

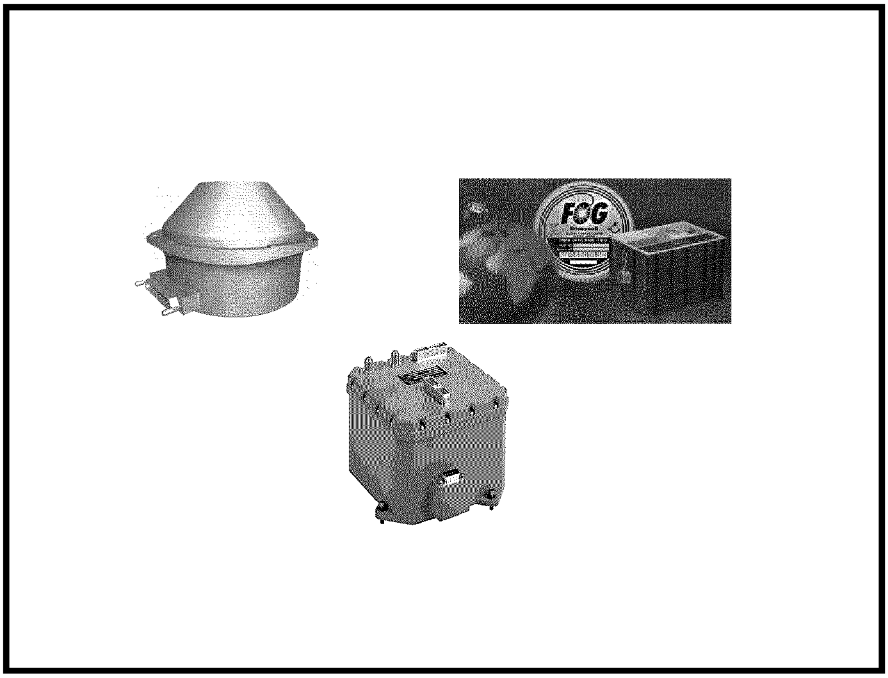


Figure 8. Sampling of New or Proposed Tactical Grade INS Systems